

X-rays and Cosmology

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Abstract. The role of X-ray observations for cosmological studies and conclusions is briefly explored. X-rays currently yield cosmologically interesting results on the abundances, evolution and gas content of clusters of galaxies, on the clustering and evolution of active galaxies and on the X-ray Background. They are unlikely in the long term future to give the most precise values of the cosmological parameters, although in the short term the baryon fraction of clusters and the Sunyaev-Zeldovich effect will remain important determinants and checks for some parameters. X-rays will however continue to play an important role in studying the astrophysics of the formation and growth of black holes, galaxies, groups and clusters. It is possible that this role will be crucial, if winds from active galaxies are responsible for breaking the simple gravitational scaling laws for clusters.

1 Introduction

X-ray observations have in the past played a minor, but important role, in cosmology. For example, the hot intergalactic medium prediction of the Steady State theory failed because the observed intensity was too low (Gould & Burbidge 1963). More recently, estimates of the gas fraction in clusters, which is dominated by the X-ray emitting intracluster medium, have shown that the matter density of the Universe is significantly below the critical value for closure (S White et al 1993; D White et al 1995).

X-rays may not be the best means to quantify the cosmological parameters (H_0 , Ω_m , q_0 , Λ etc). Of course we should continue to do our best, but it is unlikely that X-ray results will ever supercede those expected from anticipated studies of the Cosmic Microwave Background. At present they supplement such work (e.g. Bridle et al 1999; Bahcall et al 1999).

Cosmology for many of us is not, though, just the study of the geometry of the Universe, or of the inflation era, but involves the study of what has happened since redshifts of, say, 10. It involves the *astrophysics* of the baryons in this recent era, and working out how stars, black holes, galaxies and clusters arose and why. From that point of view, X-rays will be vital, since much of the dissipation in galaxy formation occurs at (soft) X-ray emitting temperatures; the X-ray emitting intracluster and intragroup medium is a living fossil, or calorimeter of the enrichment and energy injection history of galaxies; the central black holes in galaxies may only be clearly studied from their penetrating X-ray emission,

and the isotropy of the X-ray Background may be guide to the development of structure. The deepest, and the most extended, gravitational potential wells in the Universe are potent X-ray emitters.

I shall not in this introductory talk discuss the possible X-ray detection of most of the baryons in the local Universe through the study of groups, since this is covered by R Mushotzky; nor shall I explore the implications of the fluctuations in the X-ray Background, which are covered by X Barcons. Mainly I shall discuss some issues which I have been working on and which illustrate the main theme of this Conference.

2 Clusters and Cosmology

Clusters are the most massive virialized objects in the Universe and so their number density is a key diagnostic of the cosmic power spectrum, on a scale of about 8 Mpc, σ_8 . The evolution of their numbers, and particularly of the numbers above a particular intracluster gas (virial) temperature, is a good guide to the mean matter density in the Universe, Ω_m (Eke et al 1998). Current work suggests that if there is any evolution out to redshifts of about one, then it is very small (Ebeling 1999). The existence of the X-ray luminous EMSS cluster 1054-0321 provides a strong argument that Ω_m is significantly less than one (Gioia et al 1998).

Together with radio or microwave observations, X-ray intensities yield interesting constraints on the Hubble constant through the S-Z effect. The common occurrence of cooling flows at the centres of clusters, and recent working on ageing the flows (Allen et al 1999), indicates the merger history of cluster cores and gives a clue to possible baryonic dark matter.

Perhaps the most striking application of X-rays has been through the baryon fraction,

$$f_b = \frac{\text{mass of baryons}}{\text{total mass}} = \frac{\Omega_b}{\Omega_m}.$$

Since Ω_b is known fairly well from the combination of cosmic nucleosynthesis and deuterium abundance work, Ω_m is well determined from X-ray cluster studies (White & Frenk 1991). The value found is about 0.3.

Many clusters have now been carefully observed and their gas fractions determined out to r_{500} or more. Specifying a radius is important as the fraction appears to rise with radius, from about 10 per cent in the core to about 20 per cent at r_{500} , within which the mean cluster density is 500 times that of the Universe. In a sample studied by Ettori and myself (1999), we find that the gas fraction drops with redshift as $(1+z)^{1.5}$, which is surprisingly steep given the lack of evolution seen in other properties. It is explained by our use of $q_0 = 0.5$ when determining r_{500} (Sasaki 1996: for an isothermal cluster the gas mass $M_g \propto nr^3$, which since $L \propto n^2 r^3$ means that $M_g \propto L^{1/2} r^{3/2} \propto D_A$, where D_A is the angular diameter distance of the cluster, then since the total mass $M_T \propto Tr \propto D_A$, we have $M_g/M_T \propto D_A^{3/2}$). If we adjust q_0 (thus D_A) so that the gas fraction is constant

with redshift, then we find that $q_0 < 0.1$, in other words it provides a strong case for a low matter density Universe ($\Omega_m < 0.2$). Why it gives a lower value than that found via cosmic nucleosynthesis is not clear, however.

A further cosmologically interesting result from cluster studies with X-rays is that of scaling, particularly for the luminosity – temperature relation. From gravitational collapse alone, we expect that $L_x \propto T_x^2$ (the virial radius $r_v \sim r_{200}$, defined as for r_{500} above, within which the mean density of all clusters is the same at the formation redshift, therefore $Mr_v^{-3} = \text{const}$ and since $T_x \propto Mr_v^{-1}$ from the virial theorem, then $T_x \propto r_v^2$; then since $L_x \propto n^2 T_x^{1/2} V$ and the mean density of clusters n is constant, then $L_x \propto T_x^2$). The observations however indicate T_x^3 over the range $kT_x \sim 2 - 8$ keV. At higher temperatures it appears to level off more to T_x^2 (Allen & Fabian 1998) and is steeper at lower temperatures.

A major implication of this departure from the expected scaling is that significant amounts of heat have been injected into clusters. Wu, Nulsen and I (1999) find it difficult to explain this in terms of supernova heating (but see Loewenstein 1999). Of course supernovae have enriched the intracluster medium in metals, but is likely that much of their heat was radiated from the interstellar medium of their host galaxies. If it was not then supernovae can hardly provide the feedback required for galaxy formation to result in the galaxies seen today rather than many small dense ones. We also investigated widespread cooling as a way of removing low entropy gas from cluster cores and also preheating to give an entropy floor to cluster gas (Ponman et al 1999). None appears to be sufficient.

We also investigated the limits that the 1/4 keV intensity of the X-ray Background gives to galaxy formation (Wu, Fabian & Nulsen 1999; see also Pen 1997). The intensity predicted without any heat source apart from gravity is about an order of magnitude greater than that observed. Again a significant heat source is required, this time in all objects exceeding a few times 10^{12} solar masses. The total heat requirement to solve both the soft X-ray background problem and the scaling one is about 3 keV per particle, which is high.

A possible and perhaps plausible heat source is winds from active galaxies, an issue I return to near the end. If a significant fraction of the power expected from the formation of the local mass density of massive black holes emerged in winds, as well as radiation, then the problems are solved.

An implication of this is that the intergalactic medium may also have this mean energy, either in heat or potential energy, and so be much more difficult to detect than predicted by Cen & Ostriker (1999).

3 Active Galaxies and the X-ray Background

The X-ray Background (XRB) is the sum of all the X-ray emission in the recent Universe. Since the spectrum in the 2–10 keV band is flatter than known classes of source, it is most probable that it is the sum of many obscured active galactic nuclei (AGN). This explanation arose over ten years ago (Setti & Woltjer 1989)

and has been explored in detail since (Madau, Ghisellini & Fabian 1994; Celotti et al 1995; Matt & Fabian 1994; Comastri et al 1995; Wilman & Fabian 1999). A simple comparison of the XRB spectrum with that of an unobscured AGN, with a typical photon index of 2, demonstrates that *most accretion in the Universe is obscured* (Fabian et al 1998; Fabian & Iwasawa 1999).

A robust estimate of the accretion power in the Universe, assumed to be from AGN, can be obtained by assuming that the intensity of the XRB at 30 keV is emitted by an underlying power-law and yet least affected by photoelectric absorption (Fabian & Iwasawa 1999). Matching that to the spectral energy distribution of an unobscured AGN (see e.g. Elvis et al 1994), then allows the absorption-corrected energy density from accretion to be determined, ε_{AGN} . It can be increased by a correction for Compton thick objects (where $N_{\text{H}} > 1.5 \times 10^{24}$), by a factor of 1.3 (Maiolino et al 1998) to perhaps as much as 2. Then Soltan's (1982) argument can be used to convert to an expected mean mass density in black holes now;

$$\rho_{\text{BH}} = \frac{(1 + \bar{z})\varepsilon_{\text{AGN}}}{0.1c^2},$$

where $z \sim 2$ is the mean redshift of the AGN, and an accretion efficiency of 0.1 has been assumed. The result is about half the mass density found by Magorrian et al (1998) and is in good agreement with van der Marel's (1999) value (see also Salucci et al 1999). It means that most of the mass of black holes is due to radiatively efficient, but obscured, accretion. Most, about 85 per cent, of the accretion power has been absorbed and presumably reradiated in the infrared. The total radiated power from AGN can be seen from the IR backgrounds (e.g. Fixsen et al 1998) to then be about one quarter (give or take a factor of two) of that from stars.

Note here that X-rays are the only radiation which penetrates the absorber directly and so can discriminate and inform us of the actual evolution of AGN and their black holes. The radiation is absorbed at other wavelengths and so provides no direct information on the central source. It is likely that this also applies to the cores of most galaxies, which are the oldest parts. X-ray observations are likely to be crucial to understanding the accretion history of the Universe and of the evolution of the dense cores of galaxies. If the black holes in them formed very early and have always been obscured, then X-rays may become important for studying the earliest objects.

There may be an intimate connection between the formation of a galaxy spheroid and its central black hole (Silk & Rees 1998; Fabian 1999). If part of the gas forming the spheroid remains as cold obscuring gas clouds, instead of rapidly forming stars, and if the central black hole grows by accretion and blows a wind, then it may blow away the gas, and end the growth of both the black hole and the spheroid when it becomes massive and powerful enough. This scenario means that the main growth phase of the black hole is obscured, and it only becomes unobscured when the fuel supply is blown away. It then lasts for a disk

emptying time, which may be say 10 per cent of its original lifetime. As the gas is blown away it may be seen as a broad absorption line quasar.

The implication here is that AGN have powerful winds, especially when they accrete near the Eddington limit. We have seen from the cluster discussion that such powerful winds can provide an explanation for the excess energy in clusters. Thus the total power of AGN and the excess heat in clusters may be intimately linked in this way.

4 Conclusions

X-ray observations enable the thermal content and enrichment of the baryons in the Universe to be studied. The cooling of gas in the potential wells of galaxies, groups and clusters also emits predominantly in X-rays. They are the best direct probe of the accretion history of AGN, the integrated energy of which may be up to 50 per cent of that from stars.

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